

Mapping quark confinement by exotic particles

According to our increasing understanding of quark physics, more kinds of particles should exist than are presently known. New experiments at the Jefferson Laboratory are setting out to search for these particles.

In the early 1970s, evidence that the masses of strongly interacting particles increased with their internal angular momentum led the Japanese theorist Yoichiro Nambu to propose that the quarks inside these particles are "tied" together by strings. Today the string theories that emerged from this idea are being examined as candidates for the ultimate theory of nature.

Meanwhile, we have learnt

that the strong interactions are instead described by quantum chromodynamics (QCD), the field theory in which quarks interact through a "colour" force carried by gluons. Although it is therefore not fundamentally a string theory, numerical simulations of QCD ("lattice QCD"; July p23) have demonstrated that Nambu's conjecture was essentially correct: in chromodynamics, a string-like chromoelectric flux tube forms between distant static colour charges. This leads to quark confinement – the potential energy between a quark and the other quarks to which it is tied increases linearly with the distance between them. The phenomenon of confinement is the most novel and spectacular prediction of QCD – unlike anything seen before.

The ideal experimental test of this new feature of QCD would be to directly study the flux tube of figure 1 by anchoring a quark and antiquark several femtometres apart and examining the flux tube between them. In such ideal circumstances, one of the characteristics of the gluonic flux tube would be the model-inde-

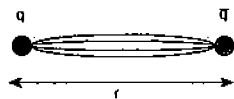


Fig. 1. (left) In quantum chromodynamics (QCD), a confining flux tube forms between distant static charges. This leads to quark confinement – the potential energy between (in this case) a quark and antiquark increases linearly with the distance between them.

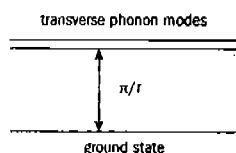


Fig. 2. (right) Model-independent spectrum of the glue (flux tube) of figure 1 – r is the quark-antiquark separation.

pendent spectrum shown in figure 2. There are two initially excited longest wavelength vibrations with identical energies, because the motion of the flux tube is in the two symmetrical dimensions perpendicular to its length.

Particles with gluons

Such a direct examination of the flux tube is of course not possible, so in real life we have to be content with systems in

which the quarks move. Fortunately, we know both from general principles and from lattice QCD that an approximation to the dynamics of the full system which ignores the impact of these two forms of motion on each other works quite well – at least down to the mass of the charm quark.

To extend the flux tube picture to yet lighter quarks, requires models, but the most important properties of this system are determined by the model-independent features described above. In particular, in a mass region around $2 \text{ GeV}/c^2$, a new kind of particle must exist in which the gluonic degree of freedom of mesons is excited.

The smoking gun characteristic of these new states is that the vibrational quantum numbers of the string, when added to those of the quarks, can produce a total angular momentum J , a total parity (or mirror-inversion symmetry) P , and a total charge conjugation (or quark-antiquark interchange) symmetry C not allowed for ordinary quark-antiquark states. These unusual J^{PC} combinations, like

The Hall D Spectrometer Conceptual Design

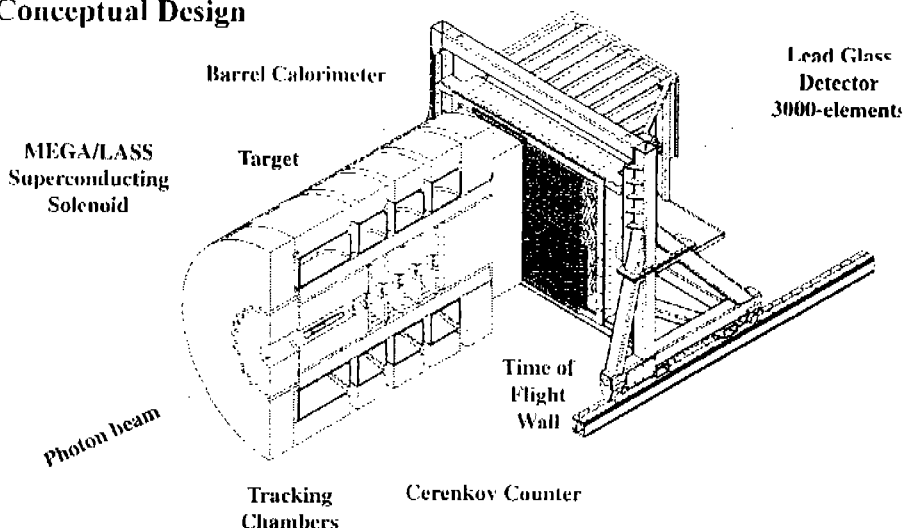


Fig. 3. The Hall D Spectrometer. A conceptual design of the proposed detector to study the photoproduction of mesons in the mass region around $2 \text{ GeV}/c^2$.

0^{++} , 1^{+-} , and 2^{+-} , are called exotic, and the states referred to as exotic hybrid mesons.

Not only general considerations and flux tube models, but also first-principle lattice QCD calculations require that these states are in this mass region, while also demonstrating that the levels and their orderings will provide experimental information on the mechanism which causes the colour flux tube to form. Moreover, tantalizing experimental evidence has appeared over the past several years for exotic hybrids as well as for gluonic excitations with no quarks at all (glueballs).

For the past two years a group of 80 physicists from 25 institutions in seven countries has been working on the design of the definitive experiment to map out the spectrum of these new states required by the QCD confinement mechanism. This experiment is part of the planned 12 GeV upgrade of the CEBAF complex at Jefferson Lab, Newport News, Virginia.

Looking for exotic hybrids

Photon beams are expected to be particularly favorable for the production of the exotic hybrids. The reason is that the photon sometimes behaves as a vector meson (a quark-antiquark state with the quark spins parallel, giving total quark spin $S = 1$). When the flux tube in this $S = 1$ system is excited to the levels shown in figure 2, both ordinary and exotic J^{PC} are possible. In contrast, when the quark spins are antiparallel ($S = 0$), as in pion or kaon probes, the exotic combinations are not generated.

To date, most meson spectroscopy has been done with incident pion, kaon or proton probes. High flux photon beams of sufficient quality and energy have not been available, so there are virtually no

data on the photoproduction of mesons below a mass of $3 \text{ GeV}/c^2$. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found.

The detector in Jefferson Lab's new Hall D is optimized for incident photons in the 8–9 GeV energy range in order to access the desired meson mass range. A solenoidal spectrometer allows for the measurement of charged particles with excellent efficiency and momentum determination while at the same time containing the shower of unwanted electron-positron pairs associated with the photon beam.

Photons will be produced using the "coherent bremsstrahlung" technique, whereby a fine electron beam from the CEBAF accelerator is passed through a wafer-thin diamond crystal. At special orientations of the crystal, its atoms can be made to recoil together from the radiating electron, boosting the emission at particular photon energies and yielding linearly polarized photons.

With the planned photon fluxes of $10^7/\text{sec}$ and the continuous CEBAF beam, the exper-

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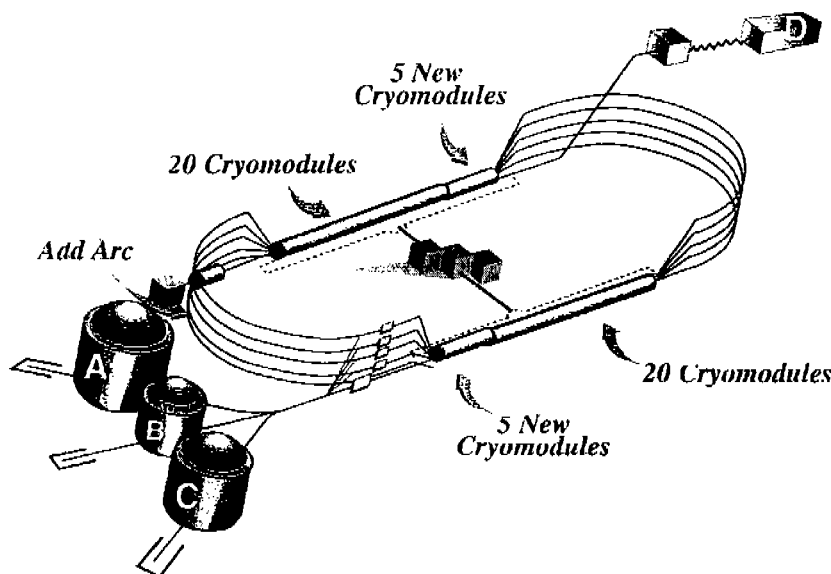


Fig. 4. The current CEBAF multi-pass electron machine at the Jefferson Lab, Newport News, Virginia, showing the existing three experimental Halls (A, B and C) and the planned Hall D.

iment will accumulate statistics during the first year of operation which will exceed extant data with pions by at least an order of magnitude. With this detector, the high statistics and the linear polarization information, it will be possible to map out the full spectrum of these gluonic excitations.

A committee chaired by David Cassel (Cornell) and consisting of Frank Close (Rutherford), John Domingo (Jefferson), William Dunwoodie (SLAC), Donald Geesaman (Argonne), David Hitlin (Caltech), Martin Olsson (Wisconsin) and Glenn Young (Oak Ridge) reviewed the project in December 1999. They concluded that the project is "well suited for definitive searches for exotic states that are required according to our current understanding of QCD." They further pointed out that because of the exceptional quality of the beams at Jefferson Lab, the laboratory is uniquely suited for carrying out such studies.

In order to achieve the required photon energy and flux with coherent bremsstrahlung, a 12 GeV electron beam is required. Figure 4 shows the current CEBAF complex with the existing three experimental halls (A, B and C) and the planned Hall D. The addition of state-of-the-art accelerating units ("cryomodules") in the linear sections of the accelerator, along with upgrading the arc magnets, will increase the electron energy from the current maximum of 5.5 GeV to 12 GeV.

When the spectrum and decay modes of these gluonic excitations have been mapped out, we will have made a giant step forward in understanding one of the most important new phenomena discovered in the 20th century - quark confinement.

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